Velocity Profile Measurement of Solid Particles Using LED as a Light Source

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***Abstract*—Optical sensors have been widely available and used in medical applications and industries for decades. Its design comes in a wide range of varieties where each are tailored based on its type, use, size, nature of investigated materials *etc*. In this work, we focus on the development and investigation of an optical sensing module, which uses Light Emitting Diode (LED) as the light source and LED photosensor as detector. This sensor is to measure the velocity of a solid particle in a gas flow inside a closed pipe. Various factors such as power dissipation, wavelength of the light source, switching time and cost are considered in the design process of this sensor. The cross correlation technique is used to determine the flow rate where small particles were introduced in a natural gas flow and they went through two distanced sets of sensor module. The LED beam source in the first set of sensor will be scattered when the particle crosses it then the corresponding photodetector will collect the light signal received and generates a pulse signal. The second pulse signal is generated when the particle crosses the second set of sensor after an interval of time. The time interval measured is used to calculate the velocity of the flow. An analysis of the received pulse signals is made to determine the best configurations of the sensors. At the end of this study, we were able to develop a simple, working, and cost effective sensing module.**

Keywords*—optical sensor; velocity measurement; particle droplet

I. INTRODUCTION

In various industries, it is vital to monitor the flow behavior inside closed vessels or pipes. The monitoring system can help obtaining flow information such as its rate, velocity profile and concentration profile. This information is useful in the process control where early detection of flow problem can be done and proper actions can be made in order to provide optimum flow condition.

At present, there are varieties of flow monitoring tools available and widely used such as in pharmaceutical, automation and food industries. However, most of its design is application-specific where each of it differs from the other based on its type of sensor, cost, acquisition speed, nature of investigated materials *etc*. The fast evolution and growth of process industry have simultaneously increased the need of research and development in the process monitoring system field [1], [2].

In this project, we investigate the use of optical sensing technique to measure the velocity of a solid-gas flow. Solid materials tend to flow non-homogenously [3]. Thus, its velocity is non-uniform and varies with time. Although solid-gas flow is common in industries, there are still no successfully built solid flow measurement devices to date [4]. Most industries that involve solid-gas flow still use traditional method to monitor processes. For example, in the rice processing industry, rice grains are manually weighed before and after the rice enhancement stage to determine the production loss due to non-optimum flow condition. The weighing often stalls the production rate as it is done manually and uses human labour [5]. A real-time monitoring system would adequately improve the production rate as it provides early detection of flow problems such as flow blockage or overspeed of grains thus, adjustments could be made accordingly.

Optical sensors are prominently used in various process monitoring modalities. Their fast response, simplicity and reliable performance are attractive benefits to be brought in this project. In addition, the sensors' sensitivity is indifferent to the component distributions of investigated material, assuming all particles being measured are opaque [6]. Thus, their sensitivity is equal regardless of the sensors' position around the pipe.

Numerous researches on process imaging were done using Light Emitting Diodes (LEDs) based optical sensors, especially in developing optical tomography systems [7] – [11]. From these previous works, we learned that the image acquisition time is often inversely proportional to the image resolution quality. Hence, in this project, we investigate the use of a simpler yet moderately faster sensing module in order to obtain the particle velocity in a solid-gas flow. The cross correlation technique employed in these previous works will be adapted in this study.

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II. Sensor Design

Several factors were taken into consideration while designing and configuring the sensing module. This chapter will explain the design stage of this sensor.

A. Velocity Measurement Technique

In principle, the cross-correlation technique traces a recognizable marker in the flow and measures its progress time along the pipe. A twin-plane sensor set is placed at the periphery of the pipe where the first sensor plane (upstream sensor) is in a fixed distance from the second sensor plane (downstream sensor). Both sensors will convert the obtained light signals to electrical signals.

In general, there are two types of cross-correlation method, which are Pixel-to-Pixel (PTP) and Sensor-to-Sensor (STS) [10]. The STS correlation directly calculates the correlation between the upstream and downstream signals. Meanwhile, the PTP correlation reconstructs the cross-sectional image in both planes then calculates the lag of each corresponding pixel of the reconstructed images.

The STS correlation is much faster (2 x N calculations for an N x N orthogonal sensor pairs) than the PTP correlation (N^2 calculations for an N x N orthogonal sensor pairs), but lacks in term of accuracy. The STS correlation is chosen to be employed in this project.

In cross-correlation technique, the particles flowing through the downstream sensor is assumed as the time-delayed replica of the ones that passed through the upstream sensor. Although the arrangement will change slightly in practice, there is still a recognizable part of the pattern conveyed between the sensors. The right distance between the two sensors is thus crucial in order to obtain an optimum sensor output. Close-distanced sensors will ensure the similarity between particles arrangement in both sensor planes but, the data acquisition time should also be considered. An investigation will be carried out in this work in order to obtain the optimum distance between the two sensors.

B. Optical Sensor

1) Transmitter

LED provides numerous advantages compared to its alternatives, for example: low power consumption, low heat generation thus long operating life, and fast switching speed. It exists in both visible colors light and infrared (invisible light). The wavelength of visible lights is in the range of 38 – 750 nm. Although the visible lights make the alignment between sensor's transmitter and detector procedure easier, they are vulnerable to perturbations due to surrounding lights, which will affect the sensors' accuracy. Infrared LEDs will be used in this work, as they are less prone to environmental disturbances. The wavelength for infrared is in the range of 400 – 700 nm.

LEDs with plastic packaging are chosen in this project over the metal LEDs as they are cheaper, give 40% more output power, and have less power dissipation rating [12]. Metal LED header allows the chip's power output to radiates into the opaque wall, thus lessen its total output. The high thermal impedance of metal, which results in higher power dissipation rating have also made the metal header less advantageous compared to plastic header.

2) Receiver

The receiver sensors have to be compatible with the transmitters. Both receiver and transmitter must be in the same wavelength range. The angle of half intensity must also be the same or greater than the emitter. This selection is guided by the manufacturer guideline of the transmitter. Two options are available for the receiver sensor type: photodiode or phototransistor. The device design of photodiodes allows them to have a better switching time compared to phototransistors. Based on the need of the fast response in this project, the photodiode is selected as a receiver. In addition, in term of cost, the photodiode is cheaper than phototransistor.

C. Sensor Projection Arrangement

There are two principal types of sensor projection arrangement that have been introduced in optical sensing [10]: parallel beam mode and fan beam mode. The parallel beam mode is a simple projection of a narrow-angled beam from one emitter to one receiver. Despite its simplicity, the drawback of this type of projection is the poor sensor coverage as it only detects the signal that passes through a single line. The fan beam mode offers full pipeline coverage because of the wide angle of the beam. Several receivers placed around the pipe are paired with the emitter. This arrangement results in a slower data acquisition rate compared to the parallel beam mode. Since this project aims for having a minimal acquisition rate, the parallel beam mode is chosen. Fig. 1 illustrates the projection arrangement of the sensor unit.

D. System Overview

Fig. 2 shows the block diagram of the system. In this project, a 200 mm pipeline with an inner diameter of 85 mm is used. In each sensor plane, an infrared LED transmitter (TSUS 4300) with the view angle of 32° is paired with a photodiode (TEFT 4300) with the view angle of 60°. Both types of these LEDs are 3 mm in diameter. In order to narrow down the divergent angle of the transmitting LED, ferrules with diameter of 1 mm are used as optical stoppers of each LED.

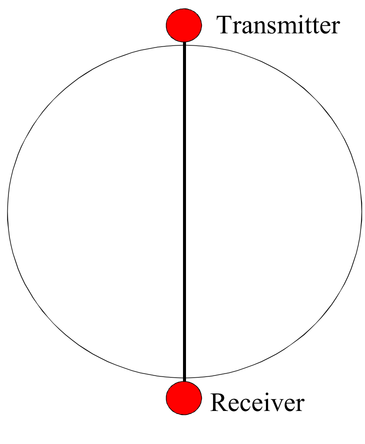

Fig. 1. Top view of sensor projection arrangment.

E. Sensor Circuit Development

A simple circuit is used as the emitter circuit as shown in Fig. 3 where a 5 V power is directly connected to the infrared transmitter. For receiver, an amplifier is used to increase the signal so that it can be measured on oscilloscope. A potentiometer is also being used in receiver circuit to enable signal manipulation of received signal. Fig. 4 shows the schematic diagram of receiver circuit.

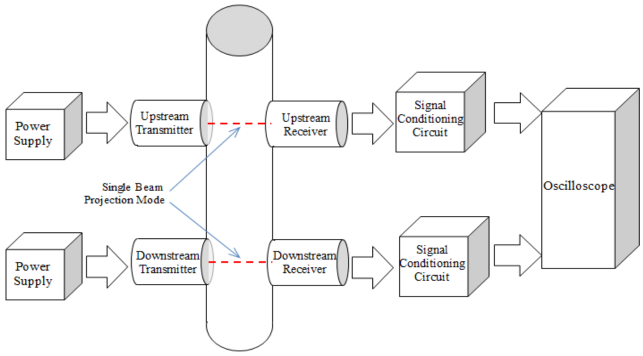

Fig. 2. Block diagram of the system.

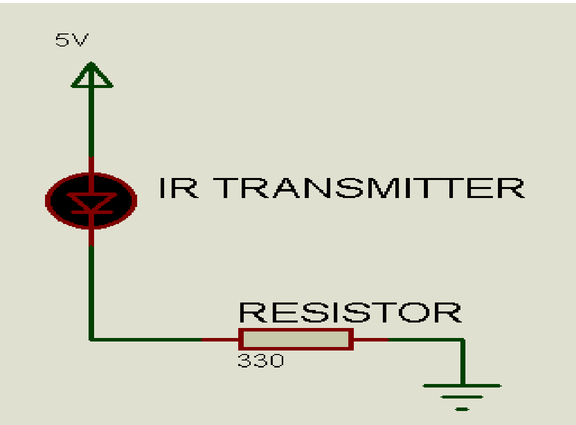

Fig. 3. Transmitter circuit.

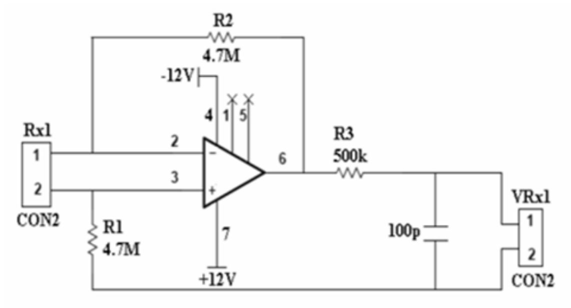

Fig. 4. Receiver circuit.

III. Methodology

The velocity of three objects will be measured using this sensing module: a ping-pong ball, a marble and a button. These objects will be dropped into the pipeline while both sensor sets are switched on. Two coaxial cables are connected to each receiver on one end and to an oscilloscope in the other ends.

The cross-correlation function of two sets of signals will be used for the flow rate measurement. In practical, the transit time, noted t, can be acquired by seeking out the time delay of two peaks of corresponding receiver's signal pulses. In order to calculate the objects' velocity, we will use the following equation where V is the velocity and D is the distance between sensors.

$$V = \frac{D}{t} \tag{1}$$

In order to use (1), we need to determine D first. As explained before, it is essential to select the correct distance between sensors. Thus, an experiment were conducted where the total output voltage of both sensors are measured when an object passes through. The sensors were placed in various distance ranged from 10 mm to 150 mm in order to determine the best distance. Fig. 5 shows the result of this experiment. We can see that the output voltage is the highest when the distance is between 10 – 50 mm. Thus, the distance between sensors of 25 mm is chosen for this project.

Once the sensors distance is set, the velocity measurement of those three objects was made. For each object, 15 measurements were made in order to verify the accuracy of this sensing module.

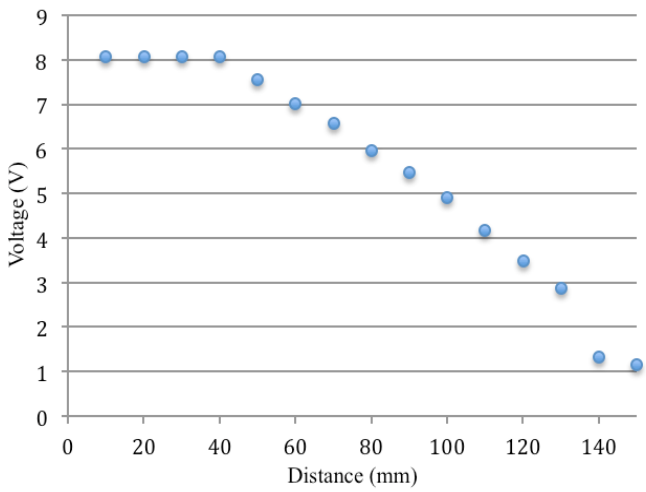

Fig. 5. Output voltage in fuction of the distance between sensors.

IV. Result and Analysis

The receiver captures the direct current transmitted by the emitter when there is no object passing through the pipe. When an object passes through, the current received is interrupted, thus creating a negative pulse signal. Fig. 6 shows the signals received by the upstream sensor (yellow line) and the downstream sensor (green line) when three objects are dropped consecutively in the pipeline. We can see that pulse signals received from both sensors are almost identical.

The distance between two corresponding signal peaks is measured using the measuring tool of the oscilloscope as shown in Fig. 7. The velocity of each object is then calculated. Table 1 shows the obtained transit times and the calculated velocities of the three objects used in this project. The velocities obtained are then plotted as shown in Fig. 8 to give a better observation of the results.

The standard deviation of obtained velocity of the ping-pong ball, marble and button after 15 measurements are 0.076 cms^{-1}, 0.071 cms^{-1} and 0.073 cms^{-1} respectively. This indicates high consistency of data obtained.

Fig. 6. Signal received from upstream sensor (yellow line) and downstream sensor (green line) when three particles flows in pipe.

Fig. 7. Measurement of transit time, *t*.

TABLE I. Measured Transit Time and Calculated Velocities

Experiment	Ping-pong ball		Marble		Button	
	Transit time, *t* (ms)	**Velocity (cm/s)**	**Transit time, *t* (ms)**	**Velocity (cm/s)**	**Transit time, *t* (ms)**	**Velocity (cm/s)**
1	140	1.786	110	2.273	115	2.174
2	130	1.923	110	2.273	120	2.083
3	130	1.923	105	2.381	120	2.083
4	135	1.852	115	2.174	110	2.273
5	125	2.000	110	2.273	120	2.083
6	130	1.923	110	2.273	115	2.174
7	140	1.786	115	2.174	120	2.083
8	125	2.000	105	2.381	120	2.083
9	140	1.786	115	2.174	110	2.273
10	140	1.786	110	2.273	120	2.083
11	135	1.852	110	2.273	110	2.273
12	135	1.852	105	2.381	115	2.174
13	135	1.852	110	2.273	120	2.083
14	125	2.000	110	2.273	115	2.174
15	135	1.852	105	2.381	115	2.174

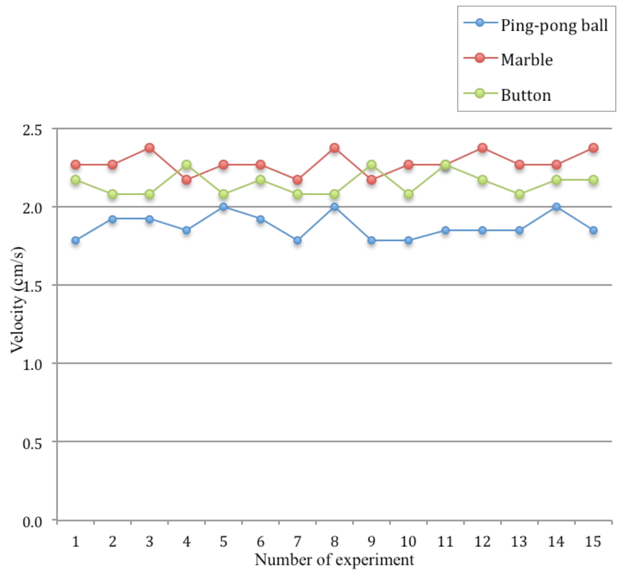

Fig. 8. Velocity of a ping-pong ball, marble and button in each experiment.

V. Conclusion

In the end of this project, we can conclude that the developed sensing module, which is simple and cost effective, is able to calculate the velocity of a particle in a solid-gas flow. The design selections of this sensor are done with the goal of having a small acquisition time. However, the velocity calculations were done manually thus had inevitably elongated the process. A development of an automatic data calculation technique and sensor manipulation such as using LabVIEW software by National Instruments would dramatically improve the data collection and calculation time.

ACKNOWLEDGMENT

Authors are grateful to the financial support by Research University Grant of Universiti Tun Hussien Onn Malaysia (ERGS Grant: E041).

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